Robotic Observations of Enhanced Carbon Biomass and Export at 55S During SOFeX

James K. B. Bishop,[1*] Todd J. Wood[1], Russ E. Davis[2] and Jeffrey T. Sherman[2]

1. Earth Sciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 90-1116, Berkeley CA, 94720. (510) 495-2457, JKBishop@lbl.gov.

2. Scripps Institution of Oceanography, La Jolla CA, 92093-0230. (858) 534 4415 rdavis@ucsd.edu; (858) 534 9863. jtsherman@ucsd.edu

More information: http://www-ocean.lbl.gov

CARBON EXPLORER

The core of the Carbon Explorer is the Sounding Oceanographic Lagrangian Observer (SOLO, S1). The SOLO is nearly neutrally buoyant relative to seawater. It adjusts it's relative buoyancy by pumping hydraulic fluid between a reservoir within its pressure case and an external inflatable bladder. Typical profiling speeds are 10 m min^{-1}.

SOLO's telemetry and operational capabilities have been greatly enhanced. We replaced SOLO's slow, unidirectional System Argos satellite communication system with much faster and bidirectional ORBCOMM telemetry. ORBCOMM transmits data at a rate of 2400 bits per second, 20 times faster than the communications system it replaced. This enables substantially more data to be relayed, has the effect of reducing biofouling problems by cutting the time spent at the surface (tens of minutes instead of days), increases operational life by reducing energy for communication (often 40% of a System Argos SOLO's energy) and permits missions which adapt to measurements taken. Improved interfaces for sensors, on board computer, and new data compression and telemetry logic schemes were also implemented.

At each surfacing, SOLO obtains a GPS fix and transmits to ORBCOMM satellites for 80 minutes. In good conditions, position and profile data transmission was usually completed within minutes; any remaining data from previous dives are transmitted in the remaining time. The SOFeX floats were programmed to profile three times per day to the surface at 0600, 1200 and 1800 hrs local solar time from depths of 1000, 300, and 300 m, respectively. Data are averaged in 5 m intervals to 250 m, 10 m intervals from 250 to 500 m, and 20 m intervals from 500 to 1000 m.

Deployed at 55S, Explorer 2104 had a near lossless data transmission performance; Explorer 1177, lost about 10% of its data due to prolonged periods of stormy weather. Explorer 2054 only transmitted about 20% of its profile data. Explorers 1177 and 2104 continued to operate for over 14 months and 375 profiles each. Explorer 2103 was deployed at 66S. Data throughput via Orbcomm falls off sharply poleward of 50 degrees north and south. Because of the communications limitation, this Explorer was profiled once per day to 1000 m. It last communicated in late July 2003, 18 months (and 227 dives) after deployment.

Carbon Explorer / Patch Relationship Revelle Survey II Feb 2002. Fig. 1S shows along track fluorescence observations by R/V Revelle mapped in the coordinate system Explorer 2104's position at the time of the third Fe addition. The third addition of Fe to the North Patch occurred almost on top of the Carbon Explorer.

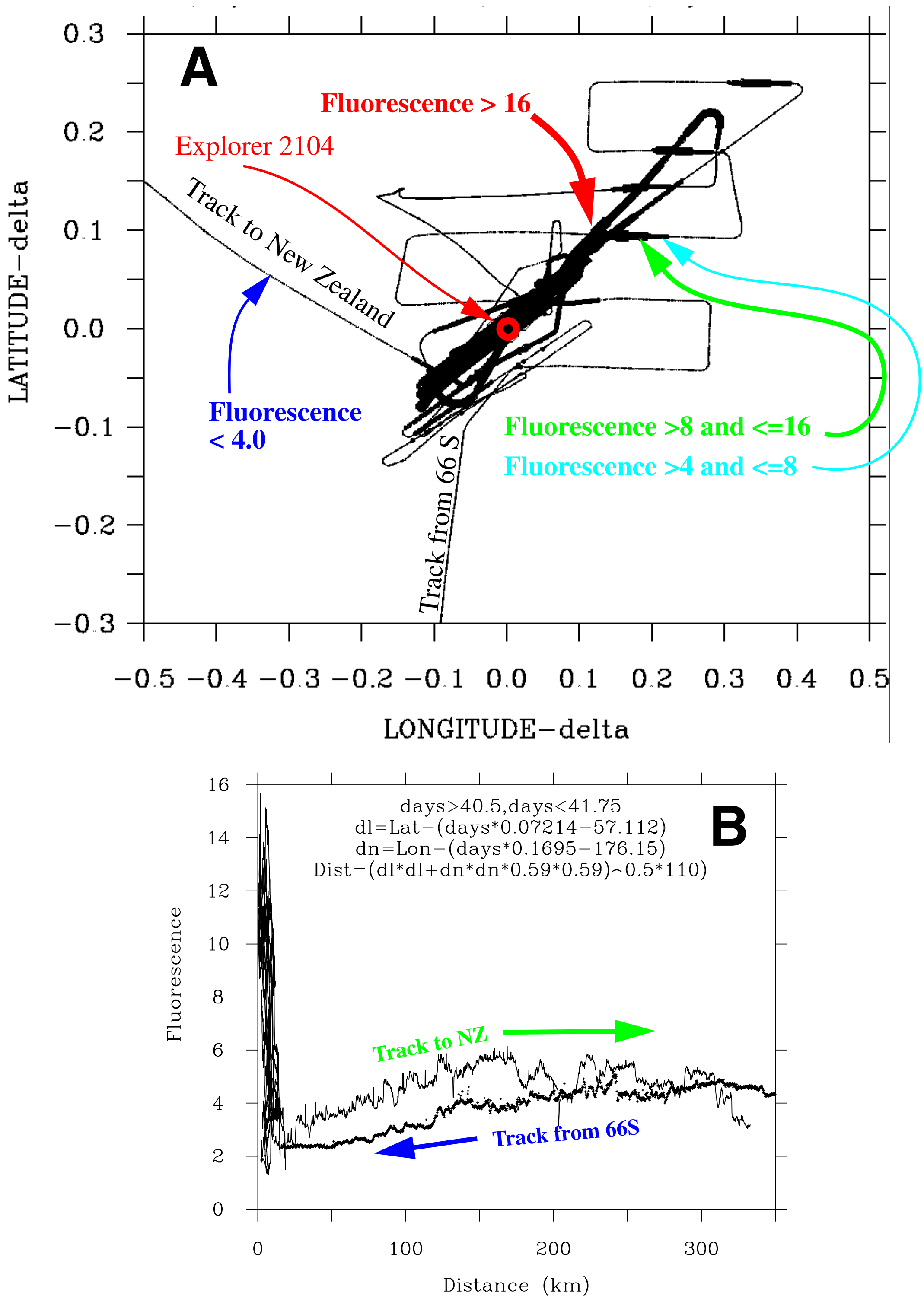


Figure 1S. Revelle Survey data in context of the "in patch" Carbon Explorer (Feb. 8 2002). A: R.V Revelle along-track Fluorescence data for UTC days 38 through 41 navigated to the positions of Explorer 2104. The Latitude and Longitude deltas are in degrees. B: Patch Fluorescence relative to surrounding waters. The "biomass" front to the northwest of the patch was a very weak feature.

SENSORS

SOLO's Seabird CTD was augmented with a new neutrally buoyant stabilized transmissometer (WETLabs, Inc. Phiolmath, OR) for the measurement of particulate organic carbon (POC). A SeaPoint light scattering sensor was added to cross-check transmissometer data and to permit investigation of the relationship between transmissometer and scattering signals. The scattering data will be analyzed and reported elsewhere.

POC sensor. Transmissometers measure the light lost from a collimated beam due to the combined effects of scattering and absorption. The stabilized 25 cm path-length transmissometer used on the Carbon Explorers operates at 660 nm (red), has a precision of better than 0.001 m^{-1}, and has a receiver acceptance angle of 1.5 degrees. During SOFeX we were able to compare beam attenuation coefficient, $\boldsymbol{c}$, values from the new 25 cm instruments with those simultaneously measured using the same 1 m path-length Sea Tech transmissometer that has been used by our group since 1981. The 1-m path length instrument has a receiver acceptance angle of 0.5 degrees.

The major components of beam attenuation coefficient are, $\boldsymbol{c_p}$ and $\boldsymbol{c_w}$ which represent contributions by particles and water, respectively. The water component, $\boldsymbol{c_w}$ is invariant and is subtracted or is removed instrumentally; absorption of light by dissolved matter is negligible at 660 nm.

Comparison of $\boldsymbol{c_p}$ data computed from our 'reference' 1-m instrument deployed during SOFeX showed that the new transmissometers were ~30% <u>less sensitive</u> to particles. This sensitivity difference is believed to be due to the three-fold difference of receiver acceptance angle. Transmissometers with wider receiver acceptance angles accept more forward scattered photons and thus have lower sensitivity. All Carbon Explorer $\boldsymbol{c_p}$ data were corrected upwards by 30% to reflect these instrumental differences and then corrected for minor biofouling effects using a reference depth of 1000 m (S4).

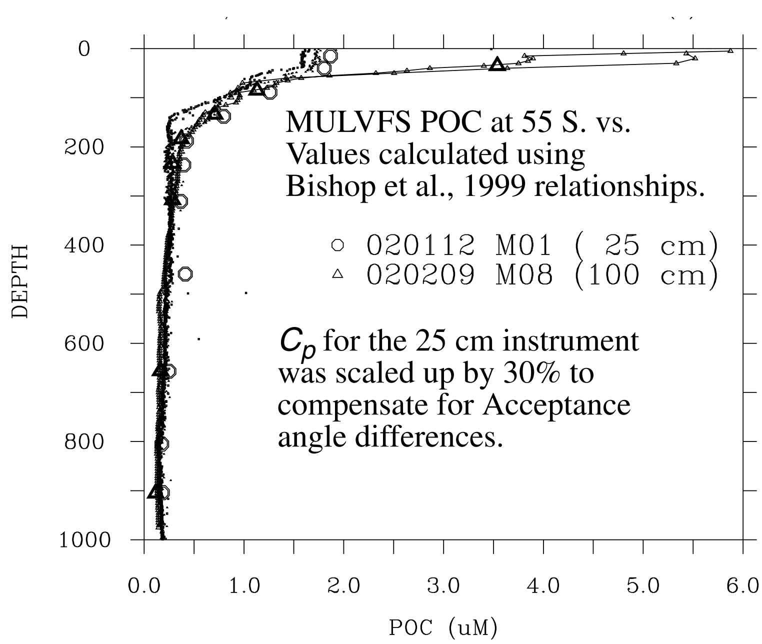


Figure 2S. Particulate organic carbon measured in MULVFS samples and estimated using transmissometer.

POC calculation. The optical detection of particulate organic carbon (POC) is based on a linear relationship found between beam attenuation coefficient, $\boldsymbol{c}$, measured at 660 nm by transmissometer and POC measured in concurrently collected size-fractionated particulate matter samples obtained using the Multiple Unit Large Volume in-situ Filtration System (MULVFS). The relationship is: POC = 16.1 ($\boldsymbol{c_p}$) µM, The conversion factor 16.1 was shown to be invariant (differences <5%) for data collected during two 2600 km US JGOFS transects of the equatorial Pacific during warm and normal phases of ENSO in 1992, and from the multi-season revisits to subarctic north Pacific waters during the Canadian JGOFS program in 1996 and 1997. Results closely agreed with similar observations in the NW Atlantic. (S3). Fig. 2S shows that the same calibration holds true during SOFeX for waters near 55S.

At 66S we found excellent correlation of c_p with MULVFS POC values but found that the POC sensor was 40% less sensitive to POC ($POC_{66S} = 27.4\ c_p$) than at 55S.

Two references below (S2 and S3) provide details and a review of other recent literature on the use of transmissometers for studies of particulate matter variability.

Comparison of MULVFS and "bottle" POC data during SOFeX. There is/has been a disagreement in the literature regarding POC measurements from bottles and in-situ pumps. Factors of 200 difference have been recently reported for the Southern Ocean (S4). We were concerned that there may be method dependent differences in calibration of beam attenuation coefficient data in terms of POC. Five 0-1000 m profiles of size fractionated particulate matter samples were obtained using MULVFS at 66S; three more were obtained at 55S. Water samples were collected from Rosette mounted bottles and filtered aboard both Revelle and Melville. The same group (Mark Altabet, David Timothy) analyzed both bottle and MULVFS samples. The MULVFS samples particles from ~1000 times more water in-situ than is filtered from water bottle samples aboard ship. Our findings during SOFeX were that POC values obtained using bottle filtration (0.7 µm Whatman GFF filters) and MULVFS (~ 1 µm Whatman QMA filters) agreed closely.

Transmissometer data from all ships and the 66S MULVFS-based calibration above was used to estimate POC. Surface layer POC values ranged from ~6 to 16 µM POC (patch days 0 to 23) and up to ~19 µM by patch day 29. Coale et al.'s (this volume) "bottle" POC numbers range from ~6 to 15 µM (patch day 2 to 23). At this level of comparison, there is no difference.

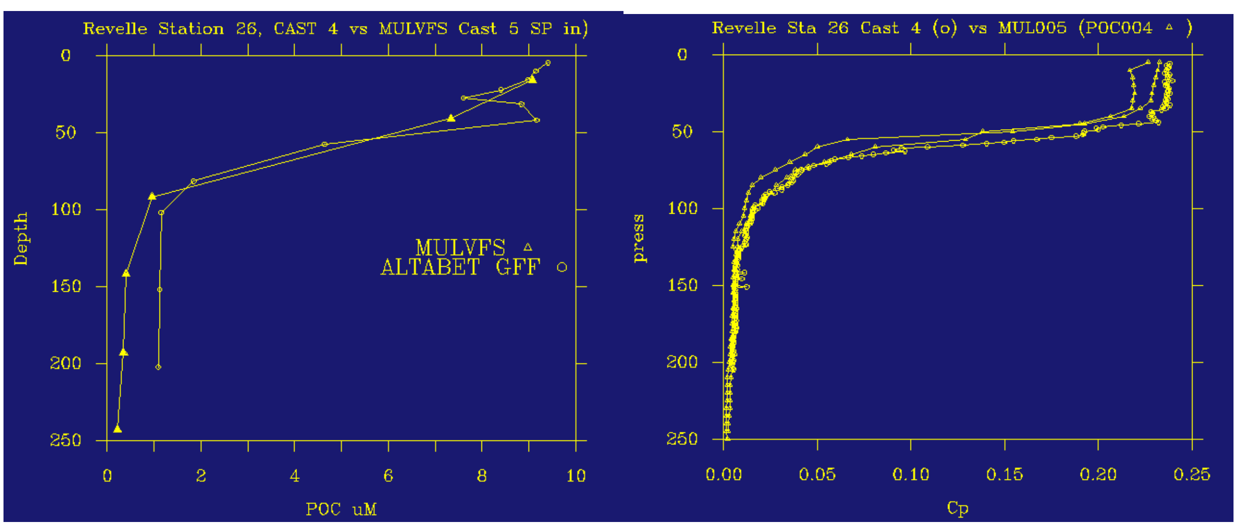


Figure S3. Left POC values from MULVFS in-situ pump system and from filtered Rosette bottle samples. Casts taken hours apart at 66S in iron amended waters.

Fig. S3 shows direct comparison of POC profiles determined using MULVFS and Rosette "bottle" samples from casts several hours apart at the same location "in the patch" at 66S (Revelle Station 26, cast 4 and Revelle MULVFS cast 5). There was almost exact agreement of POC profiles obtained by the two methods. In deeper waters there is a 0.7 µM offset in deep waters (GFF bottle filtered samples high). MULVFS data are corrected using "in-situ" blanks whereas bottle data are corrected using unused filters. Fig. S3 (right) shows c_p results from transmissometers (1.5 degree acceptance angle) deployed during the MULVFS cast (up and down traces, 6 hours apart) and the data from a similar instrument on the CTD. The particle concentration profiles were almost identical for the waters compared.

At 55S MULVFS-calibrated optically estimated POC ranges from 2 to ~9 µM (Fig. 2 of this paper). Coale *et al.* (Table) report a POC increase of 8.5+/-0.8 µM. These differences are consistent with the differences in particle retention by the filters used and a larger submicron POC pool. To summarize, there is no obvious disagreement of POC determined by bottle filtration and MULVFS at 66S; MULVFS POC's are ~20% lower at 55S, a result previously published.

Carbon Flux Index (CFI). The carbon flux index (Fig. S4) is a by-product of the Carbon Explorer POC sensor data. Between profiles, the Explorers were programmed to 'sleep' at 100 m to enhance their chance of tracking the fertilized surface waters. To minimize the likelihood of enhanced biofouling of the optical windows of the POC sensors we implemented a new scheme to periodically "blow off" the upward facing window of the sensor with the exhaust from the Explorer's Seabird CTD. This strategy clearly helped to minimize biofouling.

The "Carbon Flux Index" was derived as follows: at the end of the sleep period just before profiling is to begin, the POC sensor is warmed up for 5 minutes; a first reading is taken; then the CTD pump is energized to "wash particles from" the optics for one minute; then a final reading is taken. CFI is the difference between raw digitizer counts recorded by the two readings divided by the time that the Explorer was 'sleeping' at 100 m.

Fig. S5 shows the time integration of CFI results for Carbon Explorers 2104 and 1177. Data were normalized to the start of Explorer 2104 observations. There was little difference between control and "in patch" records until day 38 (patch day 26).

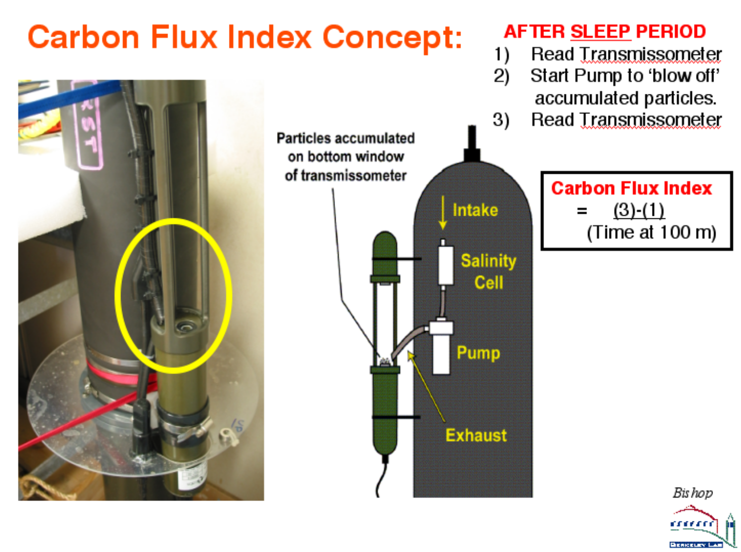


Figure S4. Carbon Flux Index Scheme as implemented on SOFeX Carbon Explorers.

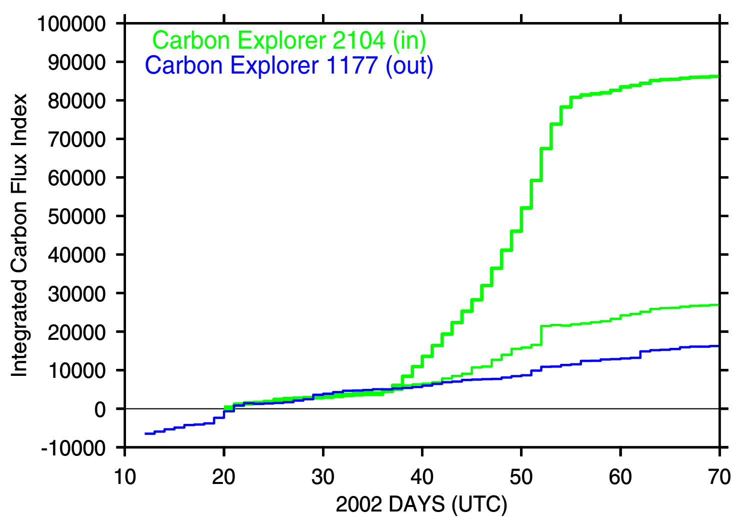


Figure S5. Integration of CFI records from Explorers 1177 and 2104. The heavier green line assumes that Explorer 2104 transiently came into contact with the sedimenting particles below the 4 km wide 250 km long patch. The North Patch developed anomalously high export between UTC days 39 and 53 of the record.

Photosynthetically active radiation (PAR). PAR is light available for biological production in the water column (Fig. S6). PAR varies with cloud cover, mixing depth, and particle concentration. It was calculated using clear sky irradiance (S5), the daily surface reflectance data retrieved from TOMS data (which includes cloud effects), and the diffuse attenuation coefficient estimated from the POC sensor. As a rough approximation, we used chlorophyll estimated from POC data and the chlorophyll - k relationship of Smith and Baker (S6). PAR was averaged over the mixed layer.

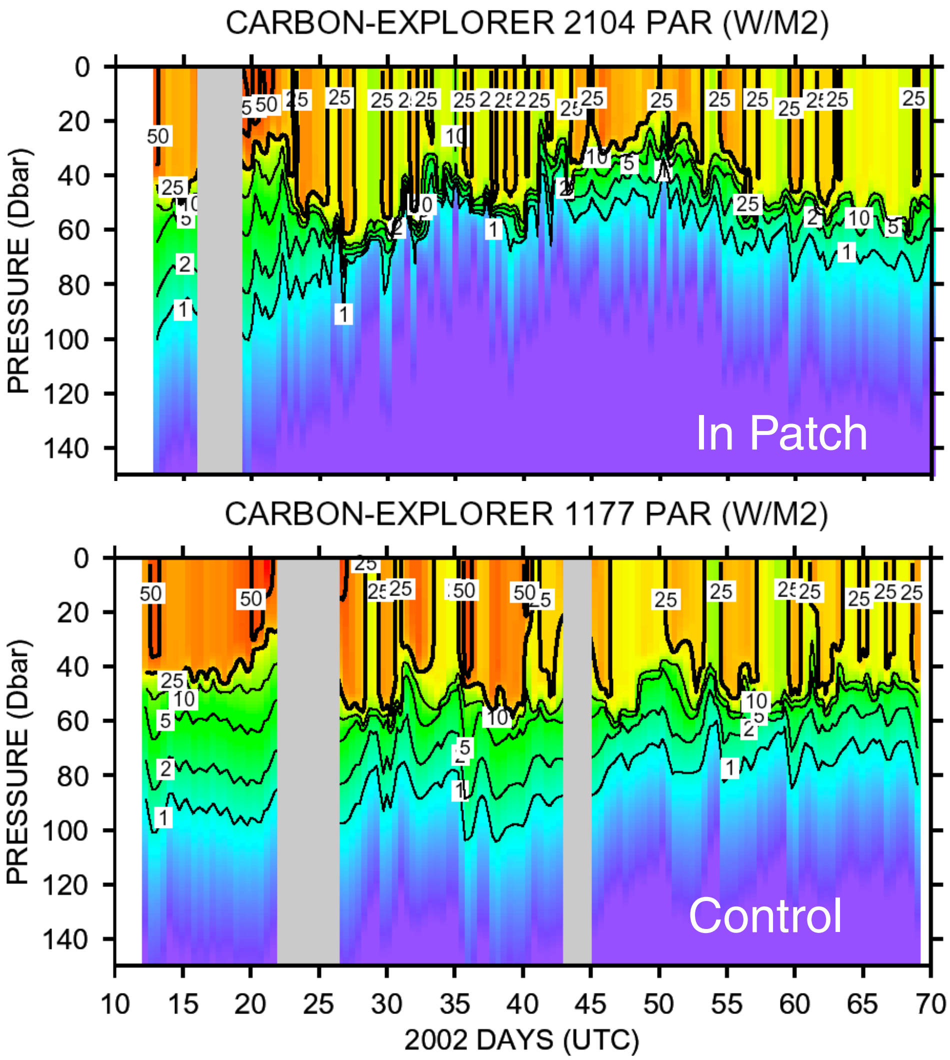


Figure S6. 24 hour averaged photosynthetically active radiation (W m^{-2}) distributions for the water columns sampled by the control and "in patch" Carbon Explorers.

Mixed layer PAR values (averaged over depth of mixing and over 24 hours) fluctuated between 10 to 50 W m^{-2} (Methods are the same as in Bishop et al. 2002; S6). In the case of iron amended waters, mixed layer PAR was attenuated compared to that of the control due to the in-growth of particles. The 1 W m^{-2} isolume penetrated to between 70 and 100 m in the control, whereas the same isolume was as shallow as 40 and 50 m 'in the patch' by February 8 2002. This isolume remained relatively shallow until early March. Beginning UTC day 41 (patch day 29), the iron - enhanced, POC-rich layer was isolated beneath the well illuminated euphotic zone.

QUIKSCAT Winds. Remotely sensed surface winds (Fig. S7) from the NASA/JPL/QUIKSCAT sensor were extracted twice per day for the locations of Carbon Explorers 1177 and 2104. Winds averaged 9 m/sec over most of the experiment (range 4 to 16 m/sec). A two day lull occurred on days 39 and 40 of the record at the time of the second Revelle Survey of the North Patch. Both Explorers experienced nearly identical forcing. There was no obvious connection between lulls in surface winds and the transiently high CFI values observed by Explorer 2104.

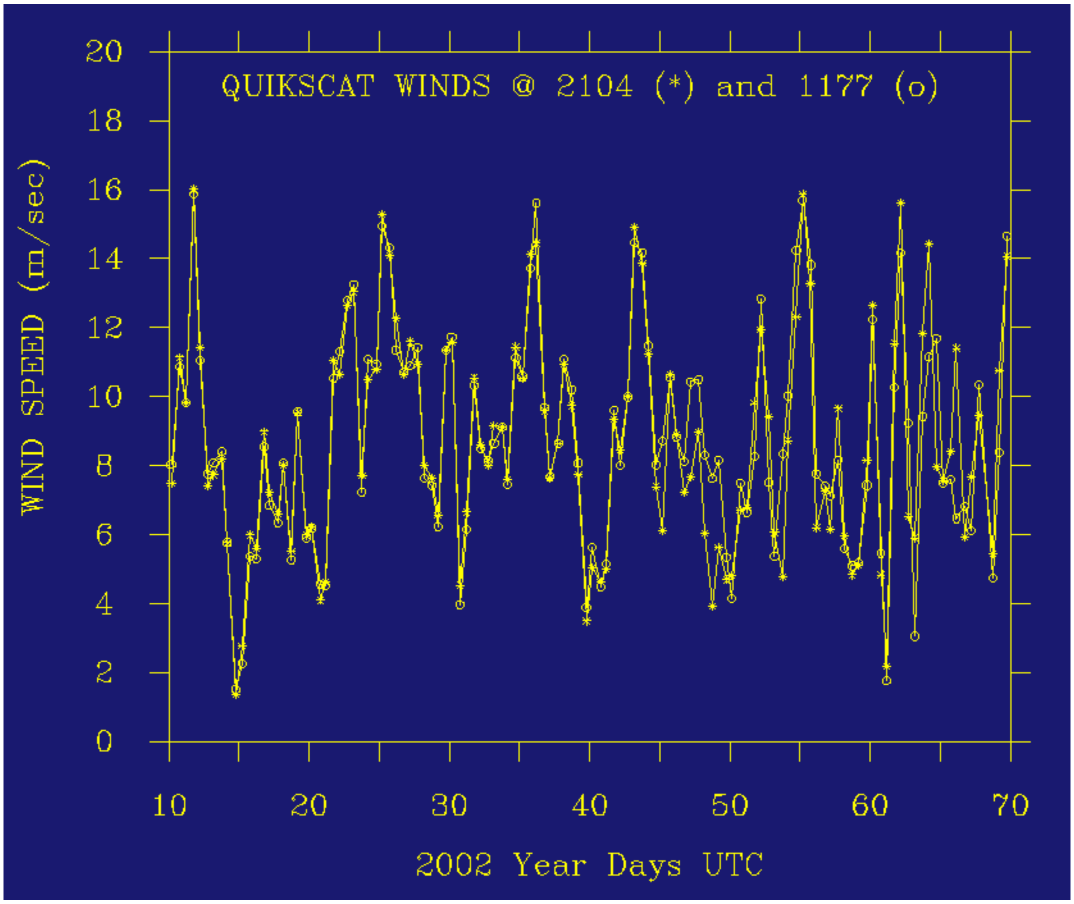
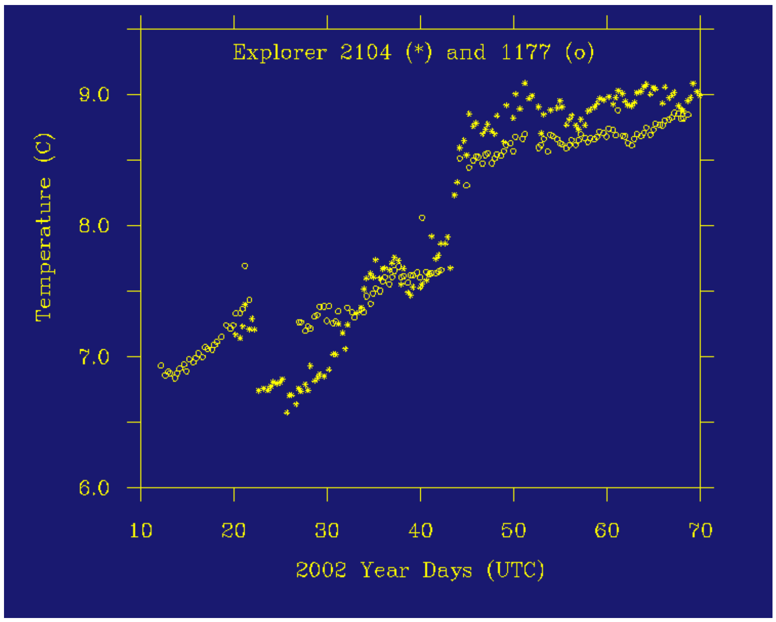


Figure S7. Remotely sensed surface winds from the NASA/JPL/QUIKSCAT sensor were extracted twice per day for the locations of the Carbon Explorers operating near 55S.

Mixed Layer Hydrography. Fig. S8 shows the mixed layer temperature and salinity time series for Explorers 2104 and 1177. Mixed layer depth is calculated as being the depth at which the potential density of water column increases by 0.05 units relative to surface values. There is little difference between the two records prior to UTC day 41. The sudden thermal shift seen in both records on ~day 22 was due to a storm event that interrupted the seasonal stratification of the mixed layer. Both floats recorded a step in temperature ~day 43 (patch day 31). Mixed layer salinity varied only from 33.96 to 34.01 over the two months with slightly higher values after day 40.



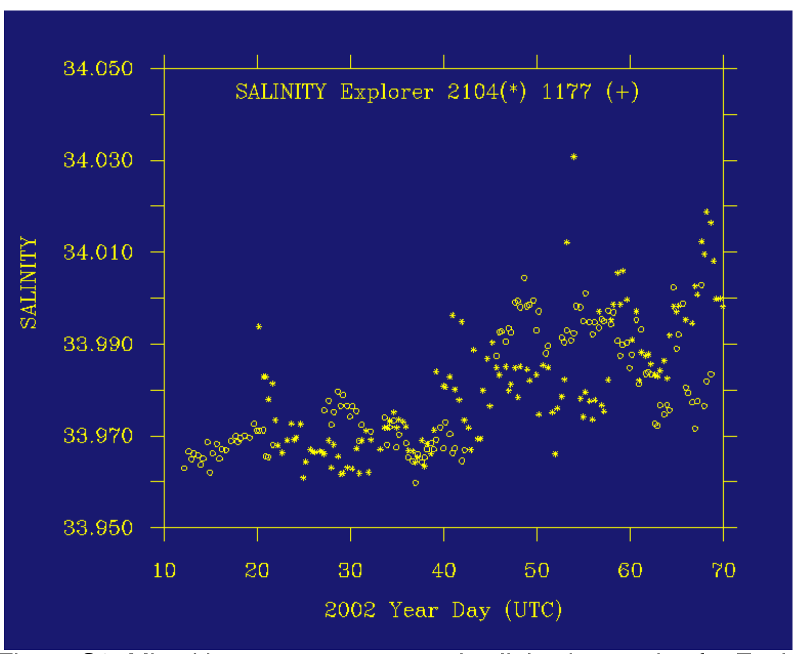
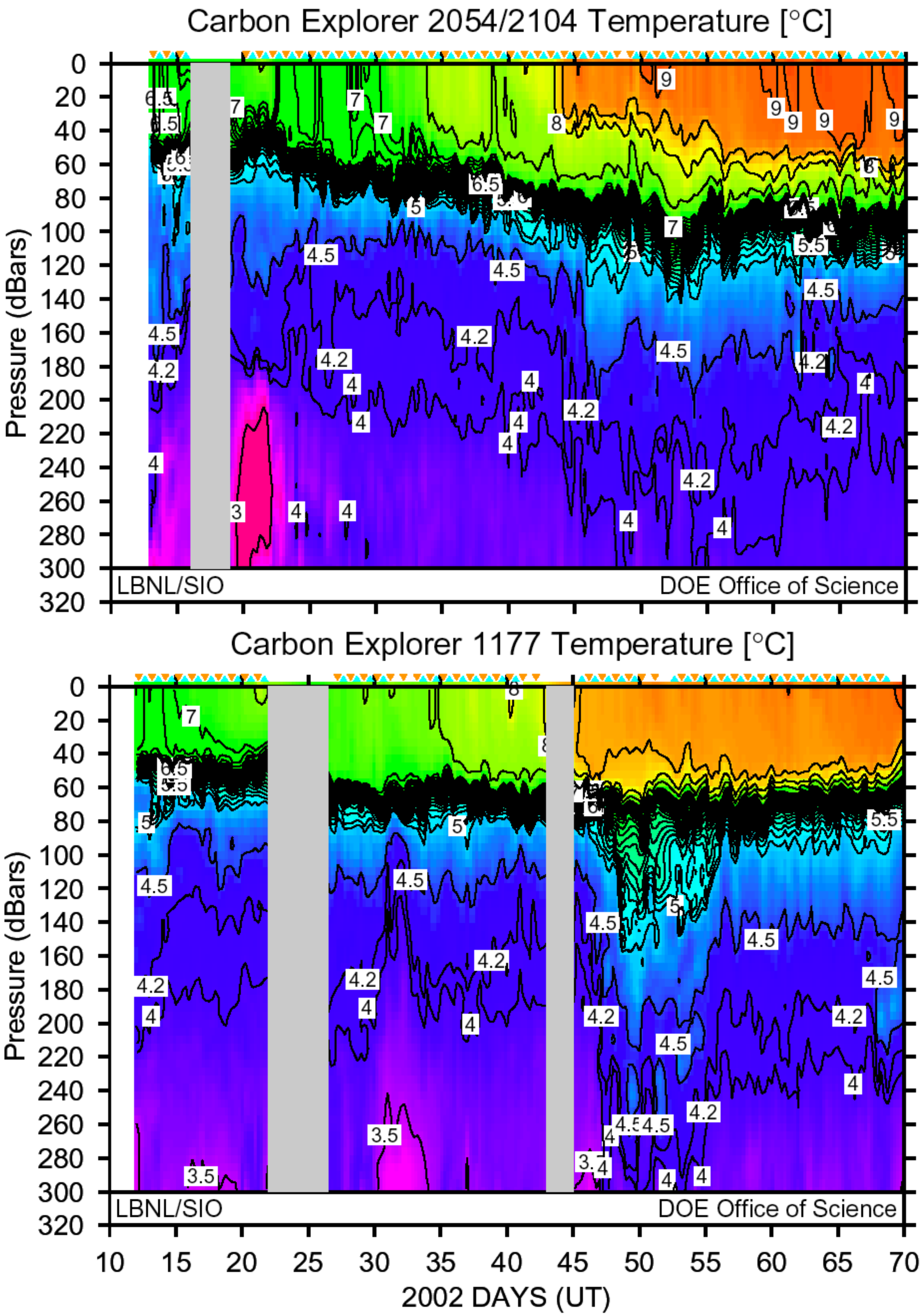


Figure S8. Mixed layer temperature and salinity time series for Explorers 2104 and 1177. Mixed layer depth is calculated as being the depth at which the potential density of water column increases by 0.05 units relative to surface values.

Temperature time series: upper 300 m.

Figure S9. Temperature for upper 300 m Carbon Explorer 2054/2104 and "Control" 1177.



Salinity time series: upper 300 m.

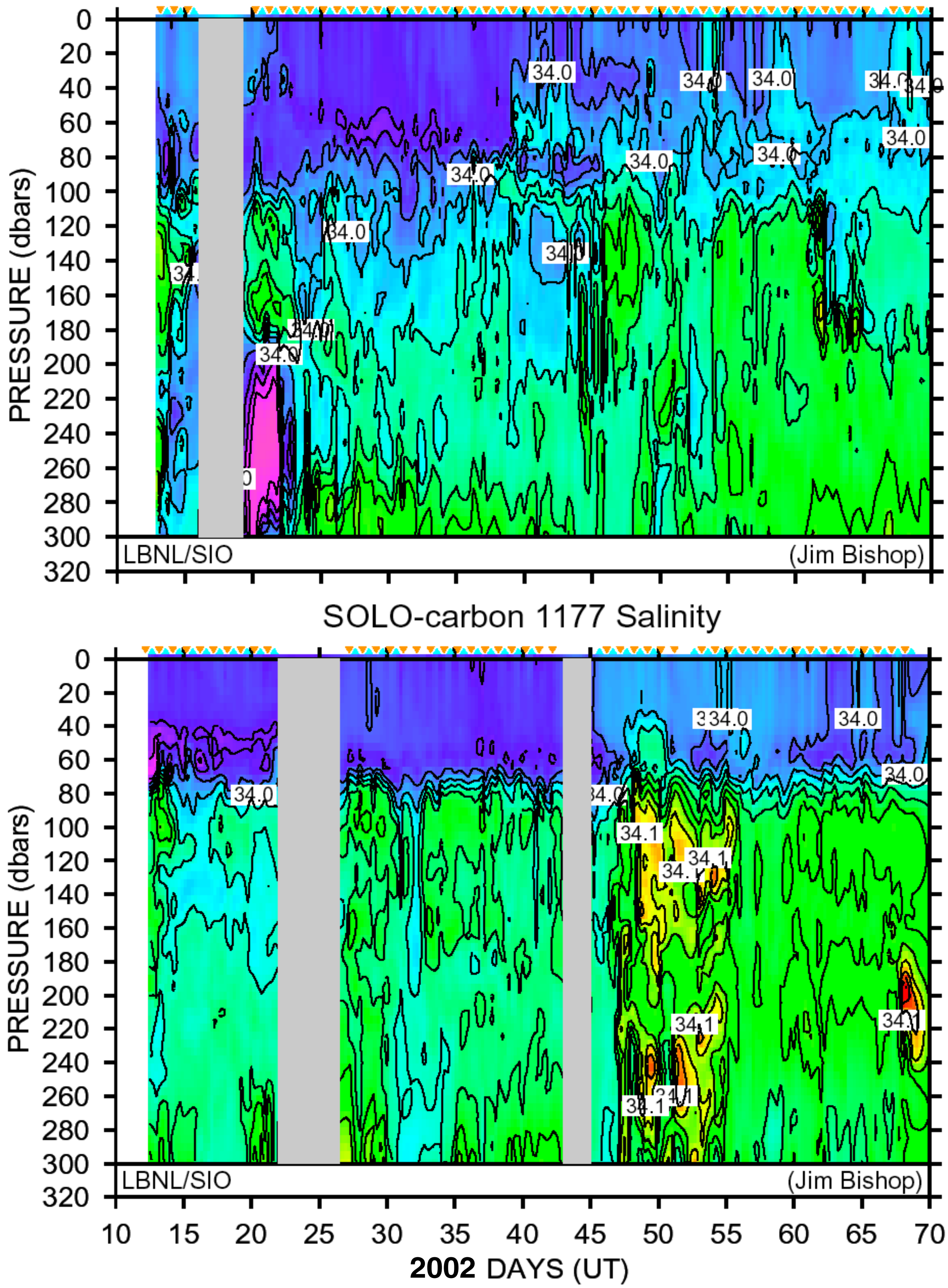


Figure S10. Salinity time series (color range 33.95 to 34.15) for "in patch" and "control" Carbon Explorers. The salinity structures below the euphotic zone have little effect on POC distributions.

Potential Density time series: upper 300 m.

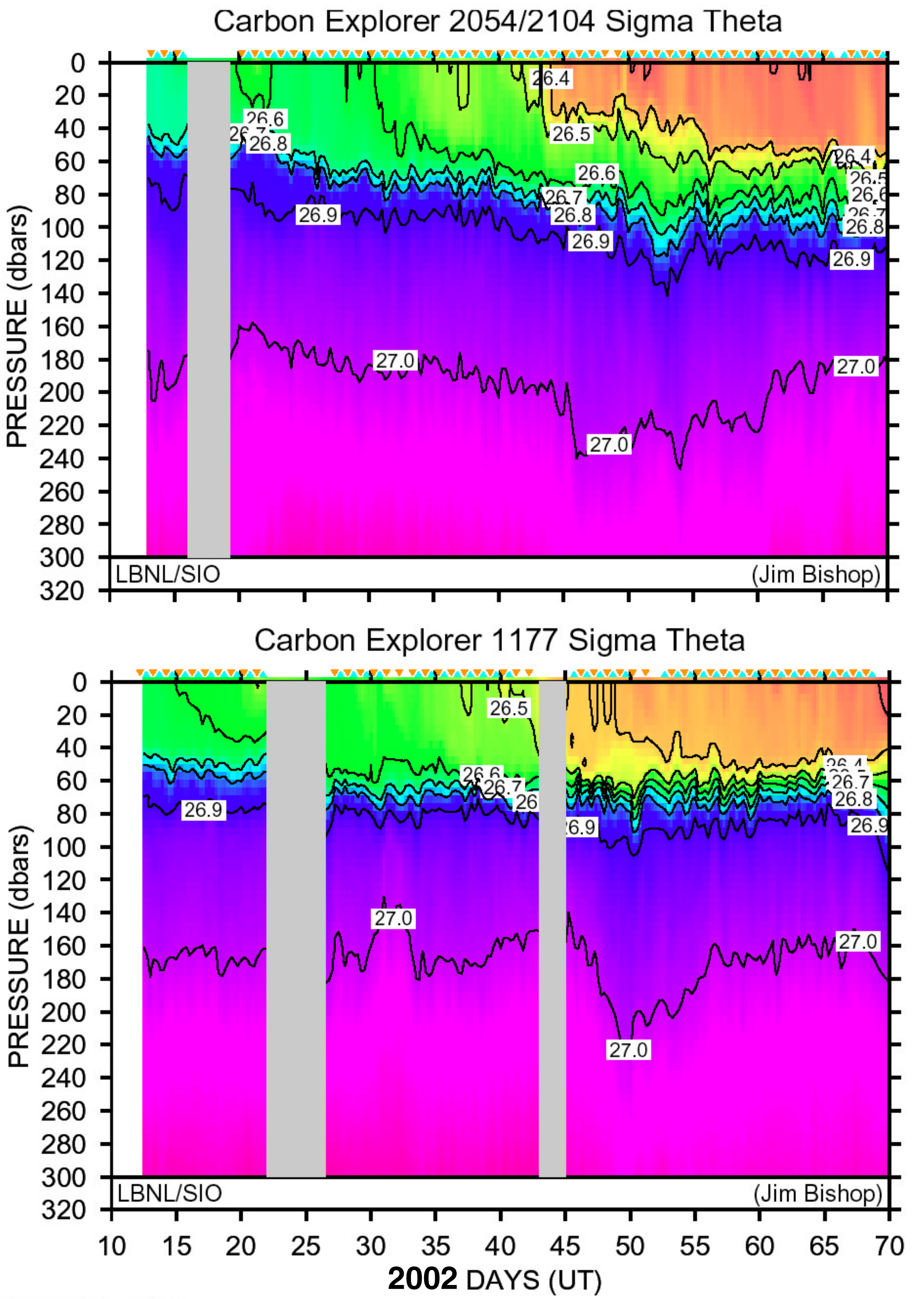


Figure S11. Potential density time series for “in patch” and “control” Carbon Explorers. The POC rich particles were in the layer with potential density of ~26.5 to 26.55 at the time they were isolated from the mixed layer.

References.

S1 R.E. Davis, J.T. Sherman, J. Dufour, *J. Atm. Oceanic Tech.*, **18**, 982 (2001)

S2 J.K.B. Bishop, S.E. Calvert, M. Y.-S. Soon, *Deep-Sea Res. II* **46**, 2699 (1999)

S3 J.K.B. Bishop, *Deep-Sea Res. I.* **46**, 355 (1999).

S4 W. D. Gardner, M.J. Richardson, C.A. Carlson, D.A. Hansell, A.V. Mishonov, *Deep-Sea Res. II*, **50**, 655. (2002)

S5 J. K. B. Bishop, W. B. Rossow, *J. Geophys. Res.* **96**, 16,839 , (1991)

S6 R. Smith and K. Baker, *Limnol. Oceanog.* **23**, 247, (1978)

S7 J. K. B. Bishop et al., *Science* **298**, 817 (2002)